DESCRIPTION

MAGNETO-RESISTIVE EFFECT MEMORY ELEMENT AND METHOD FOR PRODUCING THE SAME

TECHNICAL FIELD

The present invention relates to a magneto-resistive effect element (hereinafter, referred to as "MR"), in particular to a microscopic magneto-resistive effect element, a magneto-resistive effect magnetic head, a microscopic magneto-resistive effect memory element, and a high density magneto-resistive effect memory device including such magneto-resistive effect memory elements in a matrix.

BACKGROUND ART

A magnetic random access memory (MRAM) using a magneto-resistive (MR) film was proposed by L. J. Schwee, Proc. INTERMAG Conf. IEEE Trans. on Magn. Kyoto (1972) pp. 405. Various types of MRAMs including word lines as current lines for generating a magnetic field and sense lines using MR films for reading data have been studied. One of such studies is described in A. V. Pohm et al., IEEE Trans. on Magn. 28 (1992) pp. 2356. Such memory devices generally use an NiFe film or the like exhibiting an anisotropic MR effect (AMR) having an MR change ratio of about 2%, and thus the level of an output signal needs to be improved.

M. N. Baibich et al., Phys. Rev. Lett. 61 (1988) pp. 2472 describes that an artificial lattice film formed of magnetic films exchange-coupled through a nonmagnetic

film to each other exhibits a giant MR effect (GMR).
K. T. M. Ranmuthu et al., IEEE Trans. on Magn. 29 (1993)
pp. 2593 proposes an MRAM using a GMR film formed of magnetic
films antiferromagnetically exchanged-coupled to each
5   other. The GMR film exhibits a relatively large MR change
ratio, but disadvantageously requires a larger magnetic
field to be applied and thus requires a larger current for
writing and reading information than an AMR film.

10   One exemplary type of non-coupling GMR film is a spin
valve film. B. Dieny et al., J. Magn. Magn. Mater. 93 (1991)
pp. 101 describes a spin valve film using an
antiferromagnetic film. H. Sakakima et al., Jpn. J. Appl.
Phys. 33 (1994) pp. L1668 describes a spin valve film using
15   a semi-hard magnetic film. These spin valve films require
a magnetic field as small as that required by the AMR films
and still exhibit a larger MR change ratio than the AMR films.
Y. Irie et al., Jpn. J. Appl. Phys. 34 (1995) pp. L415
describes an MRAM, formed of a spin valve film using an
20   antiferromagnetic film or a hard magnetic film, which
performs a non-destructive read out (NDRO).

The nonmagnetic film used for the above-described
GMR films is a conductive film formed of Cu or the like.
25   Tunneling GMR films (TMR) using Al_2O_3, MgO or the like as
the nonmagnetic film have actively been studied, and MRAMs
using the TMR film have been proposed.

It is known that the MR effect provided when a current
30   flows perpendicular to the surface of a GMR film (CPPMR)
is larger than the MR effect provided when a current flows
parallel to the surface of the GMR film (CIPMR). A TMR film,
which has a relatively high impedance, is expected to provide

a sufficiently large output.

However, the tunnel junction of a TMR film has a problem in that the junction impedance gradually increases as the size of the element is reduced.

When the size of a memory cell including the tunnel junction is small to the order of submicrons, the junction impedance becomes excessively high such that the signals cannot be read. Accordingly, a tunnel insulating body capable of providing a desirable junction resistance is demanded.

When the scattering of electrons at the tunnel junction interface of the tunnel junction element is excessively strong, desirable element characteristics are not obtained. Thus, the state of the tunnel junction interface significantly influences the junction characteristics.

In a conventional TMR film, it is common to form the tunnel junction using Al_2O_3 as a nonmagnetic insulating layer. In order to obtain satisfactory insulating characteristics, such a nonmagnetic insulating layer is formed of spontaneous oxidation or plasma oxidation of a metal Al film.

However, such production methods have a possibility that a metal layer and an insulating layer are mixed in a nonmagnetic layer and a possibility that a ferromagnetic layer is also oxidized resulting in formation of an unnecessary insulating layer. These defects cause deterioration in the tunnel characteristics.

As the size of a tunnel junction element is reduced, the resistance (impedance) of the tunnel junction element is required to be decreased. It is very difficult to form a tunnel junction having a tunnel junction resistance of

5   10 $\Omega\mu m^2$ or less using Al_2O_3 as a nonmagnetic layer.

In light of the above-described problems, the present invention has an objective of providing a magneto-resistive element, a magneto-resistive effect

10 magnetic head, and a magneto-resistive effect memory element having a reduced tunnel junction resistance and an ideal tunnel junction interface; and a magneto-resistive effect memory device including such magneto-resistive effect memory elements in a matrix.

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DISCLOSURE OF THE INVENTION

A magneto-resistive effect memory element according to the present invention includes a first ferromagnetic film; a second ferromagnetic film; a first nonmagnetic film

20 film; a second ferromagnetic film; a first nonmagnetic film provided between the first ferromagnetic film and the second ferromagnetic film; a first conductive film for generating a magnetic field for causing magnetization inversion in at least one of the first ferromagnetic film and the second

25 ferromagnetic film, the first conductive film not being electrically in contact with the first ferromagnetic film or the second ferromagnetic film; and a second conductive film and a third conductive film for supplying an electric current to the first ferromagnetic film, the first

30 nonmagnetic film, and the second ferromagnetic film. The first ferromagnetic film and the second ferromagnetic film have different magnetization inversion characteristics with respect to the magnetic field, and the first nonmagnetic

film contains at least a nitride. Thus, the above-described objective is achieved.

At least one of the first ferromagnetic film and the second ferromagnetic film may contain a nitride.

At least one of the first ferromagnetic film and the second ferromagnetic film may contain a nitride which contains at least one of Fe and Co as a main component.

At least one of the second conductive film and the third conductive film may contain a nitride.

At least one of the second conductive film and the third conductive film may contain TiN.

The first nonmagnetic film may have a thickness of 0.5 nm to 4 nm.

The first nonmagnetic film may contain AlN.

The first nonmagnetic film may contain BN.

The first nonmagnetic film may contain InN.

The first nonmagnetic film may contain at least M-N-(O) where M is at least one metal element of Al, B and In, N is a nitrogen element, and (O) is an oxygen element contained in the nitride.

The first nonmagnetic film may be formed by nitriding a nonmagnetic metal material.

The first nonmagnetic film may further contain an oxide.

A method, according to the present invention, for producing the above-described magneto-resistive effect memory element includes a first step of forming the first nonmagnetic film by nitriding a nonmagnetic metal material in a nitrogen atmosphere; and a second step of oxidizing the first nonmagnetic film in an oxygen atmosphere.

At least one of the first step and the second step may be performed a plurality of times.

The method according to the present invention may further include a third step of forming the first ferromagnetic film; and a fourth step of forming the second ferromagnetic film.

The first nonmagnetic film mainly may contain M-N, and may mainly contain M-O in a grain boundary thereof.

A method, according to the present invention, for producing the above-described magneto-resistive effect memory element includes a first step of forming the first nonmagnetic film by nitriding the metal element in a nitrogen atmosphere; and a second step of oxidizing the first nonmagnetic film in an oxygen atmosphere.

At least one of the first step and the second step may be performed a plurality of times.

The method according to the present invention may further includes a third step of forming the first

ferromagnetic film; and a fourth step of forming the second ferromagnetic film.

The first nonmagnetic film may mainly contain M-N, and may also contain M-O in a dispersed manner.

A method, according to the present invention, for producing the above-described magneto-resistive effect memory element includes a first step of forming the first nonmagnetic film by nitriding the metal element in a nitrogen atmosphere; and a second step of oxidizing the first nonmagnetic film in an oxygen atmosphere.

At least one of the first step and the second step may be performed a plurality of times.

The method according to the present invention may further include a third step of forming the first ferromagnetic film; and a fourth step of forming the second ferromagnetic film.

The first nonmagnetic film may mainly include at least one M-N film and at least one M-O film, where M is at least one metal element of Al, B and In, N is a nitrogen element, and O is an oxygen element.

A method, according to the present invention, for producing the above-described magneto-resistive effect memory element includes a first step of forming the at least one M-N film by nitriding the metal element in a nitrogen atmosphere; and a second step of forming the at least one M-O film by oxidizing the metal element in an oxygen atmosphere.

At least one of the first step and the second step may be performed a plurality of times.

5   The method according to the present invention may further include a third step of forming the first ferromagnetic film; and a fourth step of forming the second ferromagnetic film.

10   An MRAM device according to the present invention includes a plurality of above-described magneto-resistive effect memory elements. A plurality of first conductive films, a plurality of second conductive films, and a plurality of third conductive films are each located in a 15 prescribed direction.

A magneto-resistive effect memory element according to the present invention includes a plurality of stacking structures; at least one first nonmagnetic film provided 20 between the plurality of stacking structures; and a first conductive film and a second conductive film for supplying an electric current to the plurality of stacking structures. The plurality of stacking structures each have a first ferromagnetic film, a second ferromagnetic film, and a 25 second nonmagnetic film provided between the first ferromagnetic film and the second ferromagnetic film. The first ferromagnetic film and the second ferromagnetic film have different magnetization inversion characteristics with respect to a magnetic field. The magneto-resistive 30 effect memory element further includes a third conductive film for generating a magnetic field for causing magnetization inversion in at least one of the first ferromagnetic films and the second ferromagnetic films

included in the plurality of stacking structures, the third conductive film not being electrically in contact with the first ferromagnetic films or the second ferromagnetic films. At least one of the second nonmagnetic films included in the plurality of stacking structures contains at least a nitride.

The first ferromagnetic films may have different magnitudes of magnetic coersive forces.

The second ferromagnetic films may have different magnitudes of magnetic coersive forces.

The at least one of the first ferromagnetic films and the second ferromagnetic films may contain a nitride.

At least one of the first ferromagnetic films and the second ferromagnetic films may contain a nitride which contains at least one of Fe and Co as a main component.

The at least one of the first conductive film and the second conductive film may contain a nitride.

The at least one of the first conductive film and the second conductive film may contain TiN.

At least one of the second nonmagnetic films may contain at least M-N-(O) where M is at least one metal element of Al, B and In, N is a nitrogen element, and (O) is an oxygen element contained in the nitride.

At least one of the second nonmagnetic films may be formed by nitriding a nonmagnetic metal material.

At least one of the second nonmagnetic films may contain an oxide.

5   An MRAM device according to the present invention includes a plurality of above-described magneto-resistive effect memory elements. A plurality of first conductive films, a plurality of second conductive films, and a plurality of third conductive films are each located in a

10   prescribed direction.

       A magneto-resistive effect element according to the present invention includes a first ferromagnetic film; a second ferromagnetic film; and a first nonmagnetic film

15   provided between the first ferromagnetic film and the second ferromagnetic film. The first ferromagnetic film and the second ferromagnetic film have different magnetization inversion characteristics with respect to a magnetic field. The first nonmagnetic film contains at least a nitride.

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       At least one of the first ferromagnetic film and the second ferromagnetic film may contain a nitride.

       At least one of the first ferromagnetic film and the

25   second ferromagnetic film may contain a nitride which contains at least one of Fe and Co as a main component.

       The first nonmagnetic film may have a thickness of 0.5 nm to 4 nm.

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       The first nonmagnetic film may contain AlN.

       The first nonmagnetic film may contain BN.

The first nonmagnetic film may contain InN.

The first nonmagnetic film may contain at least M-N-(O) where M is at least one metal element of Al, B and In, N is a nitrogen element, and (O) is an oxygen element contained in the nitride.

The first nonmagnetic film may be formed by nitriding a nonmagnetic metal material.

The first nonmagnetic film may further contain an oxide.

A method, according to the present invention, for producing the above-described magneto-resistive effect element includes a first step of forming the first nonmagnetic film by nitriding a nonmagnetic metal material in a nitrogen atmosphere; and a second step of oxidizing the first nonmagnetic film in an oxygen atmosphere.

At least one of the first step and the second step may be performed a plurality of times.

The method according to the present invention may further include a third step of forming the first ferromagnetic film; and a fourth step of forming the second ferromagnetic film.

The first nonmagnetic film may mainly contain M-N, and may mainly contain M-O in a grain boundary thereof.

A method, according to the present invention, for

producing the above-described magneto-resistive effect element includes a first step of forming the first nonmagnetic film by nitriding the metal element in a nitrogen atmosphere; and a second step of oxidizing the first
5 nonmagnetic film in an oxygen atmosphere.

At least one of the first step and the second step may be performed a plurality of times.

10 The method according to the present invention may further include a third step of forming the first ferromagnetic film; and a fourth step of forming the second ferromagnetic film.

15 The first nonmagnetic film may mainly contain M-N, and may also contain M-O in a dispersed manner.

A method, according to the present invention, for producing the above-described magneto-resistive effect
20 element includes a first step of forming the first nonmagnetic film by nitriding the metal element in a nitrogen atmosphere; and a second step of oxidizing the first nonmagnetic film in an oxygen atmosphere.

25 At least one of the first step and the second step is performed a plurality of times.

The method according to the present invention may further include a third step of forming the first
30 ferromagnetic film; and a fourth step of forming the second ferromagnetic film.

The first nonmagnetic film may mainly include at

least one M-N film and at least one M-O film, where M is at least one metal element of Al, B and In, N is a nitrogen element, and O is an oxygen element.

A method, according to the present invention, for producing the above-described magneto-resistive effect element includes a first step of forming the at least one M-N film by nitriding the metal element in a nitrogen atmosphere; and a second step of forming the at least one M-O film by oxidizing the metal element in an oxygen atmosphere.

At least one of the first step and the second step may be performed a plurality of times.

The method according to the present invention may further include a third step of forming the first ferromagnetic film; and a fourth step of forming the second ferromagnetic film.

A method, according to the present invention, for producing a metal insulating film containing at least a nitride includes a first step of forming the nitride by nitriding a prescribed metal material in a nitrogen atmosphere; and a second step of oxidizing the nitride in an oxygen atmosphere.

The prescribed metal material may be at least one of Al, B and In.

At least one of the first step and the second step may be performed a plurality of times.

A method, according to the present invention, for producing a metal insulating film including at least one M-N film and at least one M-O film where M is a prescribed metal element, N is a nitrogen element, and O is an oxygen element includes a first step of forming the at least one M-N film by nitriding the metal element in a nitrogen atmosphere; and a second step of forming the at least one M-O film by oxidizing the metal element in an oxygen atmosphere.

The prescribed metal element may be at least one of Al, B and In.

At least one of the first step and the second step may be performed a plurality of times.

A feature of the present invention is to use a nitride for a nonmagnetic insulating film, and also for a magnetic film. In this manner, a magneto-resistive element, a magneto-resistive effect magnetic head, a magneto-resistive effect memory element, and a high density magneto-resistive effect memory device including such magneto-resistive effect memory elements in a matrix, which have a reduced tunnel junction resistance and an ideal tunnel junction interface, are provided.

Especially, the nonmagnetic insulating film is formed of a combination of a nitride and an oxide. Thus, the advantage of a low tunnel junction resistance of the nonmagnetic insulating film formed of a nitride can be used. In addition, an incompletely nitrided portion of the nonmagnetic insulating film, which tends to be made as a result of dispersion in the production conditions, is

oxidized so as to increase the resistance of the incompletely nitrided portion. Thus, a leak conveying path or a hopping conveyance path can be prevented from appearing. In the case where the nonmagnetic insulating film is formed by repeating

5 a nitriding step and an oxidizing step in repetition, the controllability of the tunnel characteristics can be further improved.

According to the present invention, a low junction

10 resistance, which is equivalent to a tunnel junction resistance obtained by using Al_2O_3 for the nonmagnetic insulating film, is realized with a thicker nonmagnetic insulating film. Therefore, the MR portion can be more easily produced, which is advantageous in uniformizing the

15 characteristics of memory cells which are required to be highly integrated.

BRIEF DESCRIPTION OF THE DRAWINGS

20 Figure **1** is a cross-sectional view of a magneto-resistive effect memory cell in one example according to the present invention.

Figures **2A** and **2B** show an operation principle of the

25 magneto-resistive effect memory cell in an example according to the present invention.

Figure **3** is a cross-sectional view of a magneto-resistive effect memory cell in a example according to the

30 present invention.

Figures **4A**, **4B** and **4C** show an operation principle of the magneto-resistive effect memory cell in an example

according to the present invention.

Figure **5A** is a plan view of an MRAM in an example according to the present invention.

Figure **5B** is a partial isometric view of the MRAM in an example according to the present invention.

Figure **5C** is a partial cross-sectional view of the MRAM in an example according to the present invention.

Figure **6A** is a cross-sectional view of a magneto-resistive effect memory cell in an example according to the present invention.

Figure **6B** is a partial isometric view of an MRAM in an example according to the present invention.

Figure **7** is a cross-sectional views of a magneto-resistive effect memory cell in an example according to the present invention.

Figures **8A**, **8B**, **8C** and **8D** are cross-sectional views of a magneto-resistive effect memory cell in an example according to the present invention.

Figures **9A** and **9B** show an operation of a magneto-resistive effect memory cell in an example according to the present invention.

Figures **10A** and **10B** show an operation of a magneto-resistive effect memory cell in an example according to the present invention.

Figure **11** is a flowchart illustrating a method for producing a magneto-resistive effect memory cell in an example according to the present invention.

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Figures **12A** and **12B** are graphs illustrating characteristics of an MR portion in an example according to the present invention.

10 Figures **13A** and **13B** are cross-sectional views of a nitride film in an example according to the present invention.

Figure **14** is a flowchart illustrating a method for
15 producing a magneto-resistive effect memory cell in an example according to the present invention.

Figures **15A, 15B** and **15C** are cross-sectional views of a metal insulating film in an example according to the
20 present invention.

Figures **16A** and **16B** are cross-sectional views of a metal insulating film in an example according to the present invention.

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Figure **17** is a graph illustrating a current - voltage characteristic of a magneto-resistive effect memory cell in an example according to the present invention.

30 Figures **18A** and **18B** shows an operation of a magneto-resistive effect memory cell in an example according to the present invention.

Figure **19A** is an isometric view of an MRAM in an example according to the present invention.

Figure **19B** is a plan view of the MRAM in an example according to the present invention.

Figure **20A** is an isometric view of a magneto-resistive effect head in an example according to the present invention.

Figure **20B** is a cross-sectional view of the magneto-resistive effect head in an example according to the present invention.

Figure **21A** is a plan view of a magnetic disk apparatus in an example according to the present invention.

Figure **21B** is a cross-sectional view of the magnetic disk apparatus in an example according to the present invention.

BEST MODE FOR CARRYING OUT THE INVENTION

(Example 1)

Figure **1** shows a cross-sectional view of a magneto-resistive effect memory cell **1000** in a first example according to the present invention.

The magneto-resistive effect memory cell **1000** is a spin valve-type magneto-resistive effect memory cell using a hard magnetic film (hereinafter, referred to as an "HM spin valve-type magneto-resistive effect memory cell").

The magneto-resistive effect memory cell **1000** includes an MR portion **100**. The MR portion **100** includes a hard magnetic film **110** (second ferromagnetic film), a nonmagnetic insulating film **120**, and a soft magnetic film **130** (first ferromagnetic film). The soft magnetic film **130** is more easily magnetization-rotated by an external magnetic field than the hard magnetic film **110**. The MR portion **100** is connected with conductive films **140** and **150**. The conductive films **140** and **150** respectively act as a part of a sense line and a bit line, or vice versa. A conductive film **170** is provided above the MR portion **100** with an insulating film **160** interposed therebetween. The conductive film **170** acts as a part of a word line.

In the drawings attached to this specification, the arrows shown in magnetic films represent the directions of the magnetization of the respective magnetic films. It should be noted that the magnetization direction of each magnetic film is not limited to the magnetization direction shown in the drawings and is variable in various examples. The magnetization direction can also be changed by a write operation and a read operation.

The magneto-resistive effect memory cell **1000** operates as follows. Information is written by causing magnetization inversion of the hard magnetic film **110** by a magnetic field generated by a current which flows in the conductive film **170** (word line). Information is read by causing magnetization inversion of the soft magnetic film **130** without causing magnetization inversion of the hard magnetic film **110**. A magnetic field can be generated by supplying a current to the conductive film **140** or **150**, which acts as the sense line, in addition to the conductive film

170. In this case, it is preferable that the sense line, formed of a plurality of conductive films **140** or conductive films **150**, and the word lines, formed of a plurality of conductive films **170**, are perpendicular to each other.

Such an information write and read operation realizes a non-destructive read out (NDRO) of the magneto-resistive effect memory cell **1000**. In this case, magnetization inversion requires two magnetic field strength threshold values, i.e., a writing threshold value Hh and a reading threshold value Hs which respectively correspond to a magnetic coercive force of the hard magnetic film **110** and a magnetic coercive force of a soft magnetic film **130**.

Figures **2A** and **2B** show an operation principle of the HM spin valve-type magneto-resistive effect memory cell **1000**. A signal or data is written in the magneto-resistive effect memory cell **1000** as follows. As shown in Figure **2A**, a positive pulse current **501** or a negative pulse current **502** is caused to flow in the conductive film **170** to apply a magnetic field which exceeds the writing threshold value Hh of the hard magnetic film **110** to the hard magnetic film **110**, thus causing magnetization inversion of the hard magnetic film **110**. The level of the signal, i.e., "1" or "0" is written corresponding to the magnetization direction of the hard magnetic film **110**.

The written signal or data is read as follows. While a constant current flows in the conductive films **140** and **150** (Figure **1**), a weak pulse current is caused to flow in the conductive film **170**, thus generating a magnetic field having a strength which is equal to or more than the threshold

value Hs of the soft magnetic film **130** and is equal to or less than the threshold value Hh of the hard magnetic film **110**. The signal is read by determining whether the magnetization inversion of the soft magnetic film **130** is
5   caused or not. Specifically, the level of the signal, i.e., the data storage state is identified to be "1" or "0" by monitoring a change in the resistance value of the MR portion **100** through the conductive films **140** and **150**.

10   For example, when a current similar to the positive pulse current **501** is caused to flow in the conductive film **170** while the magneto-resistive effect memory cell **1000** is in the data storage states of "1" (Figure **2A**), the resistance value of the magneto-resistive portion **100** is not changed.
15   When a current similar to the positive pulse current **501** is caused to flow in the conductive film **170** while the magneto-resistive effect memory cell **1000** is in the data storage state of "0" (Figure **2A**), the resistance value of the magneto-resistive portion **100** increases. When a
20   current similar to the negative pulse current **502** is caused to flow in the conductive film **170**, the result is opposite to the above.

As shown in Figure **2B**, when a pulse current **503** having
25   a combination of positive and negative pulses is caused to flow in the conductive film **170** while the magneto-resistive effect memory cell **1000** is in the data storage state of "1", the resistance value of the magneto-resistive portion **100** changes from 0 to a positive value. Thus, the change ratio
30    $(\Delta R_1/\Delta t)$ is positive. By contrast, when the pulse current **503** is caused to flow in the conductive film **170** while the magneto-resistive effect memory cell **1000** is in the data storage state of "0", the change ratio $(\Delta R_1/\Delta t)$ is negative.

It should be noted that the pulse current **503** has a level which does not cause magnetization inversion of the hard magnetic film **110** but can cause magnetization inversion of the soft magnetic film **130**.

The above-described operation principle allows a signal to be read from the magneto-resistive effect memory cell **1000**. In an HM spin valve-type magneto-resistive effect memory cell such as the magneto-resistive effect memory cell **1000**, the magnetization state of the hard magnetic film **110** does not change while a signal is being read and thus an NDRO is possible.

A semi-hard magnetic film is usable instead of the hard magnetic film **110**.

The hard magnetic film **110** and the soft magnetic film **130** can be located opposite of each other. Especially when the conductive film **170** is used for applying a magnetic field to the MR portion **100**, the soft magnetic film **130** is preferably located as close as possible to the conductive film **170**.

Herein, an example of a so-called constant current mode is described, in which a change in the resistance value occurring while a constant current is applied is detected as a voltage change. Alternatively, a so-called constant voltage mode is usable, in which a change in the current level occurring while a constant voltage is applied is detected as a current change.

The structure of the magneto-resistive effect memory cell **1000** is usable as a magneto-resistive effect

element. The magneto-resistive effect element is usable as a magnetic head, and a magnetic field applied from a recording medium or the like is sensed by the MR portion **100**. The conductive film 170 can be eliminated when the MR

5   effect element is used as a magnetic head.

(Example 2)

Figure **3** shows a cross-sectional view of a magneto-resistive effect memory cell **2000** in a second

10   example according to the present invention. Throughout this specification, identical elements previously discussed with respect to the magneto-resistive effect memory cell **1000** bear identical reference numerals and the detailed descriptions thereof will be omitted.

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The magneto-resistive effect memory cell **2000** is a spin valve-type magneto-resistive effect memory cell using an antiferromagnetic film (hereinafter, referred to as an "AF spin valve-type magneto-resistive effect memory cell").

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The magneto-resistive effect memory cell **2000** includes an MR portion **101**. The MR portion **101** includes a ferromagnetic film **190** (second ferromagnetic film) exchange-coupled with an antiferromagnetic film **180**, a

25   nonmagnetic insulating film **120**, and a soft magnetic film **130** (first ferromagnetic film). The MR portion **101** is electrically connected with conductive films **141** and **150**. The soft magnetic film **130** is more easily magnetization-rotated by an external magnetic field than

30   the ferromagnetic film **190**. The conductive films **141** and **150** respectively act as a part of a sense line and a bit line, or vice versa.

A magnetic field generated by a current flowing in a conductive film **170** (acting as a part of a word line) does not cause magnetization inversion in the ferromagnetic film **190** but causes magnetization inversion only in the soft

5   magnetic film **130** which is magnetically separated from the ferromagnetic film **190** by the nonmagnetic insulating film **120**. Accordingly, information write and read is performed only by magnetization inversion of the soft magnetic film **130**. Therefore, although it is difficult to realize an NDRO,

10   there is only one magnetic field threshold value required for causing magnetization inversion and thus the operation principle is simple.

Figures **4A** and **4B** show an operation principle of the
15   magneto-resistive effect memory cell **2000**.

The ferromagnetic film **190** is exchange-coupled with the antiferromagnetic **180**, and the magnetization of the ferromagnetic film **190** is pinned in one direction.

20

A signal or data is written in the magneto-resistive effect memory cell **2000** as follows. As shown in Figure **4A**, a positive pulse current **511** or a negative pulse current **512** is caused to flow in the magnetic film **170** to apply a

25   magnetic field which is equal to or more than the reading threshold value Hs of the soft magnetic film **130** to the soft magnetic film **130**, thus causing magnetization inversion of the soft magnetic film **130**. The level of the signal, i.e., "1" or "0" is written corresponding to the magnetization

30   direction of the soft magnetic film **130**.

The written signal or data is read as follows. While a constant current flows in the conductive films **141** and

150 (Figure 3), a positive or negative weak pulse current is caused to flow in the conductive film 170, thus generating a magnetic field having a strength which is equal to or more than the threshold value Hs of the soft magnetic film 130. The signal is read by determining whether the magnetization inversion of the soft magnetic film 130 is caused or not. Specifically, the level of the signal, i.e., the data storage state is identified to be "1" or "0" by monitoring a change in the resistance value of the MR portion 101 through the conductive films 141 and 150.

For example, when a positive pulse current 513 is caused to flow in the conductive film 170 while the magneto-resistive effect memory cell 2000 is in the data storage states of "1" (Figure 4B), the resistance of the MR portion 101 is not changed ($\Delta R_2=0$). When the positive pulse current 513 is caused to flow in the conductive film 170 while the magneto-resistive effect memory device 2000 is in the data storage state of "0" (Figure 4B), the resistance of the MR portion 101 changes ($\Delta R_2 \neq 0$). When a negative pulse current (not shown) is caused to flow in the conductive film 170, the result is opposite to the above. It should be noted that the pulse current 513 has a level which does not cause magnetization inversion of the hard magnetic film 190 but can cause magnetization inversion of the soft magnetic film 130.

The above-described operation principle allows a signal to be read from the magneto-resistive effect memory cell 2000. In an AF spin valve-type magneto-resistive effect memory cell such as the magneto-resistive effect memory cell 2000, the signal which has been written is destroyed when the signal is read. Accordingly, an NDRO is

difficult to be realized.

However, the NDRO is not impossible even in an AF spin valve-type memory cell such as a magneto-resistive effect memory cell **2000**. A specific method for realizing an NDRO will be described below with reference to Figure **4C**. When a signal is read by a method of detecting a difference ΔR_3 between the resistance value of the MR portion **101** and a reference resistance value R_1, the state of the signal, i.e., "1" or "0" can be read without supplying a pulse current to the conductive film **170**. Since the signal which is written is not destroyed when being read in this case, an NDRO can be realized. The reference resistance value R_1 is preferably a value in the variable range of values of the resistance of the MR portion **101**. When a plurality of magneto-resistive effect memory cells are integrated, a resistance value of one of the plurality of magneto-resistive effect memory cells is preferably used as the reference resistance value R_1.

As an antiferromagnetic film **180**, a magnetization rotation prevention film is usable.

A laminate structure obtained by combining the ferromagnetic film **190** and the antiferromagnetic film **180**, and the soft magnetic film **130** can be located opposite of each other.

The structure of the magneto-resistive effect memory cell **2000** is usable as a magneto-resistive effect element as in the first example.

The hard magnetic film **110** (Figure 1) of the

magneto-resistive effect memory cell **1000** in the first example and the ferromagnetic film **190** (Figure **3**) of the magneto-resistive effect memory cell **2000** in the second example correspond to a pinned layer of a magneto-resistive effect element. Exemplary suitable metal and alloy materials used for the hard magnetic film **110** and the ferromagnetic film **190** include Co, Fe, Co-Fe, Ni-Fe, and Ni-Fe-Co. Specifically, Co, Fe and a Co-Fe alloy are suitable for obtaining a high MR ratio, and thus Co, Fe or a Co-Fe alloy is preferably used for an interface between the hard magnetic film **110** or ferromagnetic film **190** and the nonmagnetic insulating film **120**.

The nonmagnetic layer **120** is preferably formed of an insulating material of a nitride. More preferably, in order to improve the compatibility at the interface, the hard magnetic film **110** and the ferromagnetic film **190** are also formed of a nitride of Co, Fe or Co-Fe.

XMnSb (X is preferably at least one element selected from the group consisting of Ni, Pt, Pd and Cu) has a sufficiently high magnetic polarization ratio and thus provides a sufficiently high MR ratio when used in an MR effect element.

Exemplary suitable oxide magnetic materials used for the hard magnetic film **110** and the ferromagnetic film **190** include MFe_2O_4 (M is preferably at least one element selected from the group consisting of Fe, Co and Ni). MFe_2O_4 is ferromagnetic up to a relatively high temperature. Co-rich or Ni-rich MFe_2O_4 has a higher resistance value than Fe-rich MFe_2O_4. Co-rich MFe_2O_4 has a relatively large magnetic anisotropy. The hard magnetic film **110** and the

ferromagnetic film **190** having desirable characteristics can be obtained by adjusting the composition ratio of the components.

5   The soft magnetic film **130** preferably has a thickness of about 1 nm or more and about 10 nm or less. When the soft magnetic film **130** is too thick, the MR ratio is reduced due to a shunt effect; whereas when the film is too thin, the soft magnetic characteristics are deteriorated.

10   More preferably, the soft magnetic film **130** has a thickness of about 2 nm or more and about 7 nm or less.

           A magnetization rotation prevention film used as the antiferromagnetic film **180** which is in contact with the

15   ferromagnetic film **190** can be formed of an irregular alloy such as, for example, Ir-Mn, Rh-Mn, Ru-Mn, or Cr-Pt-Mn. When the magnetization rotation prevention film is formed in a magnetic field, the magnetization rotation prevention film can be exchange-coupled with the ferromagnetic film **190**,

20   which simplifies the production process of the magneto-resistive effect memory cell **2000**. Exemplary regular alloys usable for the magnetization rotation prevention film include Ni-Mn and Pt-(Pd)-Mn. These regular alloys need to be heat-treated for regularization but have a sufficient

25   level of stability against heat. Among the regular alloys, Pt-Mn is especially preferable. Exemplary usable oxide materials include a-Fe_2O_3, NiO, or LTO_3 (L is a rare earth element excluding Ce, and T is Fe, Cr, Mn, or Co). When these materials having a relatively low level of conductivity are

30   used, the conductive film **141** is preferably located so as to be in direct contact with the ferromagnetic film **190** as shown in Figure 3.

The soft magnetic film **130** of the magneto-resistive effect memory cells **1000** and **2000** in the first and second examples corresponds to a free layer of a magneto-resistive effect element. Exemplary suitable materials for the soft magnetic film **130** include Co, Co-Fe, Ni-Fe, and Ni-Co-Fe alloys. Preferable Ni-Co-Fe alloys include $Ni_xCo_yFe_z$ ($0.6 \leq x \leq 0.9$, $0 \leq y \leq 0.4$, $0 \leq z \leq 0.3$), which is Ni-rich; and $Ni_{x'}Co_{y'}Fe_{z'}$ ($0 \leq x' \leq 0.4$, $0.2 \leq y' \leq 0.95$, $0 \leq z' \leq 0.5$), which is Co-rich.

The alloys having the above-mentioned compositions have a low magnetic distortion (1×10^{-5}) which is required for sensors or MR heads.

(Example 3)

Figures **5A**, **5B** and **5C** show an MRAM **3000** in a third example according to the present invention. Figure **5A** is a partial plan view of the MRAM **3000**, and Figure **5B** is a partial isometric view of the MRAM **3000**. Identical elements previously discussed with respect to the magneto-resistive effect memory cells **1000** and **2000** described in the first and the second examples bear identical reference numerals and the detailed descriptions thereof will be omitted. Herein, the MR portion **100** (or **101**) has a prism shape, but can have a circular cylinder, elliptical cylinder, truncated cone or truncated pyramid shape. A face of the MR portion **100** (or **101**) which is in contact with the conductive films **140** or the like preferably has a relationship of $L_1 > W_1$ where L_1 represents the length and W_1 represent the width in order to provide an anisotropy in shape.

Figure **5C** is a cross-sectional view illustrating a preferable cross-sectional shape of the conductive film **170**

which is more preferable for efficiently applying a magnetic field to the MR portion **100** (or **101**). In Figure **5C**, letters h and h' each represent an angle made by a side of the cross-section facing the MR portion **100** (or **101**) and another

5   side. Preferably, at least one of angles h and h' is an acute angle.

Due to the cross-sectional shape of the conductive film **170** as shown in Figure **5C**, the current flowing in the

10   conductive film **170** at a uniform density is caused to flow in the vicinity of the MR portion **100** (or **101**) in a larger amount than in the rest of the conductive film **170**. Thus, the magnetic field can be efficiently applied to the MR portion **100** (or **101**). Such a cross-sectional shape is

15   especially preferable when the aspect ratio (width/thickness) of the cross-section of the conductive film **170** is reduced due to the size reduction of the MRAM **3000**.

20   As can be appreciated from the above, the free layer in the MR **100** (or **101**) is preferably located as close as possible to the conductive film **170** in order to efficiently apply the magnetic field. Such an arrangement is preferable because it increases an operation margin for selecting an

25   MR portion in the MRAM **3000** even when a synthesized magnetic field generated by the conductive film **170** (word line) and the sense line **150** (or **140**) which are perpendicular to each other is used. This occurs because the level of the current required for causing a magnetization rotation is lowest at

30   the operation point where the strength of the magnetic field generated by the conductive film **170** (word line) and the strength of the magnetic field generated by the sense line **150** are equal to each other.

The MRAM **3000** includes a plurality of magneto-resistive effect memory cells **1000** in the first example or a plurality of magneto-resistive effect memory cells **2000** in the second example which are arranged in a matrix. The magneto-resistive effect memory cells **1000** and **2000** are CPPMR elements.

As shown in Figures **5A** and **5B**, in the MRAM **3000** including the CPPMR elements, the magneto-resistive effect memory cells **1000** or **2000** are connected parallel to each other. Accordingly, even when the number N of the magneto-resistive effect memory cells increases, the S/N ratio is not substantially reduced.

Figure **6A** is a cross-sectional view of a magneto-resistive effect memory cell **1001** according to the present invention.

The magneto-resistive effect memory cell **1001** includes an MR portion **102**. The MR portion **102** includes a hard magnetic film **111**, a nonmagnetic film **121**, and a soft magnetic film **131**. The MR portion **102** is electrically connected with conductive films **142** and **143**. The conductive films **142** and **143** respectively act as a part of a sense line and a bit line, or vice versa. A conductive film **171** is provided above the MR portion **102** with an insulating film **161** interposed therebetween. The conductive film **171** acts as a part of a word line. The magneto-resistive effect memory cell **1001** having the above-described structure is a CIPMR element.

As shown in Figure **6B**, the MRAM **3001** includes the

magneto-resistive effect memory cells **1001** connected in series. In such a case, when the number N of the magneto-resistive effect memory cells **1001** increases, the S/N ratio of the entirety of the MRAM **3001** is considered to be reduced although the MR ratio of each magneto-resistive effect memory cell **1001** remains the same.

In most of the figures in the present application, including Figures **5** and **6**, the MR portion is represented as being larger than the sense, word and other lines. This is merely for clarity, and the size relationship between the MR portion and the lines is not limited to this. In order to efficiently apply a magnetic field to the MR portion, each line preferably covers the MR portions.

The MRAMs **3000** and **3001** are memory devices using a magnetic property, and thus are nonvolatile unlike semiconductor DRAMs utilizing accumulation of charges. Unlike semiconductor flash memory devices, there is no limit in the number of times of write/read operations in principle, and a time period required for write and erase operations is short to the order of nanoseconds.

The operation principle of each magneto-resistive effect memory cell is as described in the first and second examples. For producing the MRAM **3000** or **3001**, a plurality of magneto-resistive effect memory cells **1000**, **1001** or **2000** are provided in a matrix as shown in Figures **5A**, **5B** and **6B**. Specifically, a plurality of word lines are first provided in a lattice, and then the magneto-resistive effect memory cells **1000**, **1001** or **2000** are provided respectively adjacent to intersections of the word lines. In Figures **5A**, **5B** and **6B**, the word lines (conductive film **170** or **171**) are shown

in only one direction (i.e., row direction or column direction) for simplicity and in conformity to Figures 1, 3 and **6A**. The lattice arrangement of the word lines will be described in detail in the following examples.

5

A magnetic field generated by two intersecting word lines adjacent to a selected MR portion at address (N, M) is applied to the selected MR portion. One of the two word lines can be replaced with one sense line (or one bit line).

10

In an MRAM including a plurality of magneto-resistive effect memory cells **1000** shown in Figure **1**, when a synthesized magnetic field generated by the two word lines exceeds the value of a switching magnetic field represented

15 by an asteroid-type curve of the hard magnetic film **110**, information is written. When the above-mentioned synthesized magnetic field does not exceed the value of the switching magnetic field but exceeds the value of a switching magnetic field of the soft magnetic film, an NDRO of

20 information is performed from a desired magneto-resistive effect memory cell.

In an MRAM including a plurality of magneto-resistive effect memory cells **2000** shown in Figure **3**, the

25 operation is basically the same as that of the MRAM including magneto-resistive effect memory cells **1000** in that a synthesized magnetic field causes magnetization inversion of the soft magnetic film **130** for writing information. Information stored in these MRAMs can be read in the

30 following manner. A pulse current is caused to flow in two word lines adjacent to an MR portion at address (N, M), and information stored in the MR portion is read based on a change in the resistance value which is monitored through the sense

line and the bit line connected to the MR portion.

As described with reference to Figure **4C** in the second example, an NDRO of the information stored in the MR portion at address (N, M) is realized by comparing the resistance value of the MR portion and a reference resistance value.

Alternatively, each word line and each sense line can be provided with a switching device such as, for example, a transistor. An MR portion at address (N, M) can be selected by selecting the word line of row N and the sense line (or bit line) of column M by an address designating signal.

In order to prevent an inflow of a signal pulse through another path and a return of a harmonic component caused by an increase in speed of signal pulse transfer, and thus to transfer the signal pulse efficiently, each MR portion is preferably provided with an element or a semiconductor element having a rectifying function and nonlinear and asymmetric electric characteristics. Examples of the elements having nonlinear and asymmetric electric characteristics include a diode or a transistor. Especially in order to deal with a high speed pulse response, a MOS transistor is preferably used. Use of such an element improves the selectability of magneto-resistive effect memory cells arranged in a matrix.

In this case, it is preferable to provide an element having a rectifying function and nonlinear and asymmetric electric characteristics (hereinafter, referred to as a "nonlinear element") **70** in series with the MR portion **100**, such as in a magneto-resistive effect memory cell **3100** shown

in Figure **7**. In Figure **7**, the nonlinear element **70** is provided below the MR portion **100**. Alternatively, the nonlinear element **70** can be provided above the MR portion **100**.

5

A preferable example of such a nonlinear element **70** has, for example, an M-I-S junction structure of metal (M) - insulator (I) - semiconductor (S), a P-N junction structure of a P-type semiconductor and an N-type semiconductor, or

10 a P-I-N junction structure of p-type semiconductor - insulator (I) - N-type semiconductor.

It is generally known that the characteristics of an MR portion rely on the heat-treatment temperature and

15 that some of the materials usable for an MR portion cannot provide the MR characteristics easily at a temperature of about 400°C or higher. In the present invention, the nonlinear element **70**, which is produced after the MR portion **100** is produced, is preferably formed of a material which

20 is usable at a temperature of about 300°C or lower such as, for example, a-Si (amorphous silicon).

As the density of a memory cell increases, the problem of the leakage magnetic field, which is generated

25 by the word lines, to the outside of the selected MR portion becomes more serious. In order to reduce the interference effect of the leakage magnetic field to the outside of the selected MR portion, it is preferable to cause a current pulse to flow to, in addition to one set of word lines for

30 generating a magnetic field at the address (N, M), one word line or one set of word lines which are adjacent to the above-mentioned first one set of word lines. Thus, the leakage magnetic field generated is counteracted so as to

reduce the influence of the leakage magnetic field.

A magneto-resistive effect head has a structure shown in Figures **20A** and **20B**. Figures **21A** and **21B** show a
5   hard disk apparatus including the magneto-resistive effect head (which can include a recording head and a reproduction head). A portion interposed between magneto-resistive effect element shielding layers **602** and **603** (Figure **20A**) acts as a reproduction head, and recording magnetic poles
10   **605** and **606** interposing a coil **607** therebetween act as a recording head. According to the present invention, a magneto-resistive effect head capable of high performance and high density recording can be provided by the improvement in the MR characteristics of the magneto-resistive effect
15   element. The magneto-resistive effect head will be described in detail later in a fourteenth example according to the present invention.

(Example 4)
20   Figures **8A** through **8D** are cross-sectional views of a magneto-resistive effect memory cell **4000** in a fourth example according to the present invention.

The magneto-resistive effect memory cell **4000**
25   includes an MR portion **200**. The MR portion **200** includes hard magnetic films **112**, **113** and **114**, soft magnetic films **132**, **133** and **134**, nonmagnetic insulating films **122**, **123** and **124**, and nonmagnetic films **222** and **223**. A conductive film **172**, which acts as a part of a word line, is provided above the
30   MR portion **200** with an insulating film **162** interposed therebetween.

The MR portion **200** includes a plurality of soft

magnetic film/nonmagnetic insulating film/hard magnetic film structures stacked with a nonmagnetic film interposed between each structure of the plurality. In the magneto-resistive effect memory cell **4000**, three such structures are stacked. The number of such structures is optional.

In the fourth example, the hard magnetic films **112**, **113** and **114** have different magnetic coercive forces, and as a result, there are a plurality of magnetic field threshold values for writing. Accordingly, four different levels of a signal can be stored in one magneto-resistive effect memory cell **4000**. The magnetic coercive force of each of the hard magnetic films **112**, **113** and **114** can be changed by changing the composition or the thickness of the respective film. As shown in Figure **8A**, by a method of detecting a difference ΔR_4 between the resistance value of the MR portion **200** and a reference resistance value R_2, the four levels of the signal stored (e.g., "0", "1", "2" and "3") can be read.

Since the magneto-resistive effect memory cell **4000** includes three soft magnetic film/nonmagnetic insulating film/hard magnetic film structures, there are four patterns of magnetization directions as shown in Figures **8A** through **8D**. Accordingly, four levels (e.g., "0", "1", "2" and "3") can be stored in one magneto-resistive effect memory cell **4000**.

Information is written in the magneto-resistive effect memory cell **4000** by causing magnetization inversion of the hard magnetic films **112**, **113** and **114** by a magnetic field which is generated by pulse currents **521**, **522** and **523**

flowing in the conductive film **172**. In the fourth example, the magnetic coercive force of the hard magnetic film **112** is smallest and the magnetic coercive force of the hard magnetic film **114** is largest. By adjusting the level of the

5 pulse current flowing in the conductive film **172**, the hard magnetic film or films in which magnetization inversion is caused can be selected among the hard magnetic films **112**, **113** and **114**. One of the hard magnetic films **112**, **113** and **114** in which magnetization inversion is to be caused can

10 be selected by adjusting the level of the pulse current flowing in the conductive film **172**. In the example shown in Figures **8A** through **8D**, the level of the pulse current gradually increases from the state in Figure **8A** toward the state in Figure **8D**. In Figure **8A**, the level of a pulse

15 current **520** flowing in the conductive film **172** is still lower than the level of a pulse current **521** in Figure **8B**. In Figure **8A**, magnetization inversion occurs in none of the hard magnetic films; and in Figure **8D**, magnetization inversion occurs in all of the hard magnetic films.

20

Information is read from the magneto-resistive effect memory cell **4000** by a method of detecting the difference ΔR_4 between the resistance value of the MR portion **200** and the reference resistance value R_2 as described above.

25

Information can also be read by supplying a current to the conductive film **172** and reading a change in the resistance value of the MR portion **200**. In this case, the change in the resistance value of the MR portion **200** can

30 be detected by a comparison with the reference resistance value R_2.

The soft magnetic films **132**, **133** and **134** can have

different magnetic coercive forces. In such a case, many levels of the signal can be stored in one magneto-resistive effect memory cell **4000** by precisely adjusting the level of the pulse current flowing in the conductive film **172** and determining the film or films in which magnetization inversion is to be caused and the film or films in which magnetization inversion is not to be caused among the soft magnetic films **132, 133** and **134**. These levels of the signal are preferably read by a method of detecting the difference ΔR_4 between the resistance value of the MR portion **200** and the reference resistance value R_2 as described above.

Alternatively, the magnetization direction of all the hard magnetic films can be pinned, in which case the levels of the signal can be stored by causing the magnetization inversion only in an arbitrary one of the soft magnetic films as described in the second example.

(Example 5)

In a fifth example according to the present invention, a method for producing the magneto-resistive effect memory cell **1000** shown in the first example will be described.

Referring to Figure **1**, the MR portion **100** of a sandwich type was produced using, as sputtering targets, $Ni_{0.68}Co_{0.2}Fe_{0.12}$ (for the soft magnetic film **130**), Al (for the nonmagnetic insulating film **120**), and $Co_{0.75}Pt_{0.25}$ (for the hard magnetic film **110**)(the compositions are all by the atomic ratio). For sputtering, a multi-origin sputtering apparatus (not shown) was used. The basic structure of the MR portion **100** was CoNiFe (15)/AlN(1)/CoPt (10). (In such a representation of the structure, the numeral in the

parentheses represents the thickness (unit: nm), and "/" represents that the substances mentioned before and after the "/" are combined.) The thickness of each film or layer was controlled by a shutter.

AlN which is a nitride NM used for the nonmagnetic insulating film **120** was formed by sputtering Al in an $(N_2+(Ar))$ atmosphere.

CoPt for the hard magnetic film **110** was magnetized, and the MR characteristics of the MR portion **100** were measured at room temperature at an applied magnetic field of 100 Oe. The MR ratio was about 26%. The magnetic field width generated by the MR portion **100** which is represented by Hc was about 5 Oe to 100 Oe. The tunnel junction area was about 1 μm^2. The impedance of the tunnel junction was about 25 Ω. It was also found that the impedance of the tunnel junction can be controlled in the range of several ohms to several hundred ohms by changing the film formation conditions. The magneto-resistive effect memory cell **1000** shown in Figure **1** was produced including the MR portion **100** produced by the above-mentioned method. The conductive films **140** and **150** acting as a part of either a sense line or a bit line were formed of Pt or Au, and the conductive film **170** acting as a part of a word line was formed of Al, AuCr, Ti/Au or Cu/Ta. The insulating film for insulating the MR portion **100** and the conductive film **170** was formed of CaF_2, SiO_2 or Si_3N_4.

The operation of the magneto-resistive effect memory cell **1000** produced in this manner was confirmed in the following manner.

A pulse current **531** shown in Figure **9A** was caused to flow in the conductive film **170** (word line) to magnetize the hard magnetic film **110** in one direction. Then, a pulse current **532** (upper portion in Figure **9B**) was caused to flow in the conductive film **170**, and a change in the voltage value (i.e., a change in the resistance value $\Delta R_5/\Delta t$) of the magneto-resistive effect memory cell **1000** measured through the conductive films **140** and **150** (sense line and bit line) was monitored. As a result, a pulse **533** (lower portion in Figure **9B**) corresponding to the written information was detected. Thus, it was found that the desired magneto-resistive effect memory cell **1000** was realized.

(Example 6)

In a sixth example according to the present invention, a method for producing the magneto-resistive effect memory cell **2000** shown in the second example will be described.

The magneto-resistive effect memory cell **2000** shown in Figure **3** was produced by a method similar to that of the fifth example.

The MR portion **101** having a basic structure of $Ni_{0.1}Fe_{2.9}O_4$ (15)/AlN (1.2)/$Ni_{0.2}Fe_{2.8}O_4$ (5)/IrMn (25) was produced using, as sputtering targets, $Ni_{0.1}Fe_{2.9}O_4$ (for the soft magnetic film **130**), Al (for the nonmagnetic insulating film **120**), $Ni_{0.2}Fe_{2.8}O_4$ (for the ferromagnetic film **190**), and IrMn (for the magnetization rotation prevention layer as the antiferromagnetic film **180**). AlN was formed by the method described in the fifth example.

The MR characteristics of the MR portion **101** were

measured at room temperature at an applied magnetic field of 100 Oe. The MR ratio was about 24%. The tunnel junction area was about 1 μm^2.

5   The conductive films **141** and **150** were formed of Au, and the conductive film **170** was formed of AuCr. The insulating film for insulating the MR portion **101** and the conductive layer **170** was formed of SiO_2. The insulating film can be formed of CaF_2, Al_2O_3 or Si_3N_4.

10   The operation of the magneto-resistive effect memory cell **2000** produced in this manner was confirmed in the following manner.

15   A pulse current **541** shown in Figure **10A** was caused to flow in the conductive film **170** to magnetize the soft magnetic film **130** in one direction. Then, a pulse current **542** (upper portion in Figure **10B**) was caused to flow in the conductive film **170**, and a change in the voltage value (ΔV_1) of the magneto-resistive effect memory cell **2000** measured

20 through the conductive films **141** and **150** was monitored. As a result, a voltage change **543** (lower portion in Figure **10B**) corresponding to the written information was detected. Thus, it was found that the desired magneto-resistive effect memory cell **2000** was realized.

25 memory cell **2000** was realized.

(Example 7)

          In a seventh example according to the present invention, a method for producing the magneto-resistive

30 effect memory cell **2000** shown in the second example will be described.

          The magneto-resistive effect memory cell **2000** shown

in Figure **3** was produced by a method similar to that of the sixth example.

The MR portion **101** having a basic structure of
$Ni_{0.8}Fe_{0.2}$ (10)/AlN (d)/$Co_{0.75}Fe_{0.25}$ (5)/IrMn (20) was produced using, as sputtering targets, $Ni_{0.8}Fe_{0.2}$ (for the soft magnetic film **130**), Al (for the nonmagnetic insulating film **120**), $Co_{0.75}Fe_{0.25}$ (for the ferromagnetic film **190**), and IrMn (for the magnetization rotation prevention layer as the antiferromagnetic film **180**). AlN was formed by the method described in the fifth example.

Figure **11** is a flowchart illustrating a method for producing the magneto-resistive effect memory cell **2000** in this example. In this example, the magneto-resistive effect memory cell **2000** was produced as follows. The soft magnetic film **130** was formed (S11), and a nonmagnetic metal material was nitrided in a nitrogen atmosphere to form the nonmagnetic insulating film **120** (S12). Then, the nonmagnetic insulating film **120** was oxidized in an oxygen atmosphere (S13). These nitriding step and the oxidizing step were repeated a plurality of times as necessary (S14). The ferromagnetic film **190** and the antiferromagnetic film **180** were formed (S15), and the sense lines and the bit lines (conductive films **141** and **150**) and the word lines (conductive film **170**) were formed (S16). The order in which these elements are formed are arbitrarily varied in accordance with examples. For example, the ferromagnetic film **190** and the antiferromagnetic film **180** can be formed before the soft magnetic film **130** is formed. The sense lines or the bit lines (conductive film **141** or **150**) can be formed before the soft magnetic film **130** is formed.

The MR characteristics of the MR portion **101** produced were measured at room temperature at an applied magnetic field of 100 Oe. The MR portion **101** exhibited the behavior shown in Figure **12A**. In Figures **12A** and **12B**, R_0

5 indicates the standardized interface resistance ($\Omega\mu m^2$) when the nonmagnetic insulating film **120** has a thickness d_1 of 1.2 nm. ■ indicates the specific resistance (R/R_0) of the nonmagnetic insulating film **120**, and □ indicates the MR ratio (%).

10

From Figure **12A**, it was appreciated that the nonmagnetic insulating film **120** can be produced with satisfactory controllability so as to realize a desired magneto-resistive effect memory cell **2000** according to this

15 example. When the nonmagnetic insulating film **120** is excessively thin, the nonmagnetic insulating film **120** has a specific resistance which is considered to indicate an appearance of a leak conductance path. As a result of subjecting the nonmagnetic insulating film **120** (i.e.,

20 nitride film) produced by the method shown in the fifth example to heat treatment performed in an oxygen atmosphere (S13), the characteristics of the nonmagnetic insulating film **120** are changed as shown in Figure **12B**. In this manner, the nonmagnetic insulating film **120** having desired

25 characteristics was produced. It was found that when the nonmagnetic insulating film **120** is set to have a thickness d exceeding 1 nm, the reproducibility and uniformity of the characteristics of the nonmagnetic insulating film **120** are improved by repeating the AlN film formation step and the

30 subsequent oxidizing step alternately a plurality of times (S14). Accordingly, using the method for producing the nonmagnetic insulating film **120** in this example, a tunnel junction using a nitride nonmagnetic film having

satisfactory characteristics can easily be provided.

Such a method for producing a nitride nonmagnetic insulating film is applicable to any semiconductor having an insulating film as well as an insulating film of an MR portion.

The reason is that a nitride film **410** (Figure **13A**) in its entirety can have its insulating characteristics improved by oxidizing incompletely insulating portions **405**, which are included in a nitride film **400** and tend to appear mainly in a grain boundary, so that the incompletely insulating portions **405** become oxidized portions **415**.

In the case where incompletely nitrided portions **425** (Figure 13B) are included in a nitride film **420** in a dispersed manner, a leak path for conducting a current via the incompletely nitrided portions **425** in a hopping manner appears. In this case, a nitride film **430** in its entirety can have its insulating characteristics improved by oxidizing the incompletely nitrided portions **425** into oxidized portions **435**.

As a result, the oxidized portions **415** produced in the nitride film **410** and oxidized portions **435** produced in the nitride film **430** exhibit satisfactory insulating characteristics, and the nitride occupying most of the nitride films **410** and **430** governs the tunnel junction resistance characteristics. Therefore, a desired MR element can be provided. The nonmagnetic insulating film produced in this example is formed of an Al-N-(O) structure, where N is a nitrogen element and (O) is an oxygen element contained in the nitride film. Al can be replaced with a

conductive metal material such as, for example, B or In.

(Example 8)

In an eighth example according to the present invention, a method for producing the magneto-resistive effect memory cell **2000** shown in the second example will be described.

The magneto-resistive effect memory cell **2000** shown in Figure **3** was produced by a method similar to that of the sixth example.

The MR portion **101** having a basic structure of $Ni_{0.8}Fe_{0.2}$ (10)/(Al-N (d)/Al-O (D))n/$Co_{0.75}Fe_{0.25}$ (5)/PtMn (20) was produced using, as sputtering targets, $Ni_{0.8}Fe_{0.2}$ (for the soft magnetic film **130**), Al (for the nonmagnetic insulating film **120**), $Co_{0.75}Fe_{0.25}$ (for the ferromagnetic film **190**), and PtMn (for the magnetization rotation prevention layer as the antiferromagnetic film **180**). Here, d indicates the thickness of a nitride film, D indicates the thickness of an oxide film, and n indicates the number of times the nitride film and the oxide film are stacked.

Figure **14** is a flowchart illustrating a method for producing the magneto-resistive effect memory cell **2000** in this example. In this example, the MR portion **101** having the above-described structure was produced in order to further improve the controllability of the tunnel junction resistance characteristics. The soft magnetic film **130** was formed (S21). The nonmagnetic insulating film **120** was formed by first producing a nitride film **441** shown in Figure **15A** by the method shown in the fifth example (S22) and then producing an Al-O film as an oxide film **442** on the nitride

film **441** (S23). The oxide film **442** was produced by forming an Al film by sputtering and subjecting the Al film to spontaneous oxidization in a vacuum tank. This technique was best. Alternatively, the oxide film **442** can be produced by plasma oxidation of an Al metal material or by directly stacking Al_2O_3.

In this example, when the nonmagnetic insulating film **120** was set to have a thickness of 1 nm or greater, the nonmagnetic insulating film **120** was produced by stacking the nitride film **441** and the oxide film **442** a plurality of times (i.e., n = 2 or more) (S24). The value of d was set to be 0.3 to 1 nm, and the value of D was set to be 0.2 to 0.5.

Then, the ferromagnetic film **190** and the antiferromagnetic film **180** were formed (S25), and the sense lines and the bit lines (conductive films **141** and **150**) and the word lines (conductive film **170**) were formed (S26). The order in which these elements are formed are arbitrarily varied in accordance with examples. For example, the ferromagnetic film **190** and the antiferromagnetic film **180** can be formed before the soft magnetic film **130** is formed. The bit lines or the sense lines (conductive film **141** or **150**) can be formed before the soft magnetic film **130** is formed. The oxide film **442** can be formed before the nitride film **441** is formed.

In Figure **15A**, a top surface and a bottom surface of the nonmagnetic insulating film **120** are formed of the oxide film **442** and the nitride film **441**. With reference to Figure **3**, when one of the soft magnetic film **130** and the ferromagnetic film **190** interposing the nonmagnetic

insulating film **120** is formed of a nitride, it is preferable to provide the nitride film **441** on the soft magnetic film **130** or the ferromagnetic film **190** which is formed of nitride. In this way, a cleaner junction interface is obtained. When the soft magnetic film **130** and the ferromagnetic film **190** interposing the nonmagnetic insulating film **120** are both formed of a nitride, the nonmagnetic insulating film **120** is preferably formed to have the structure shown in Figure **15B**. In the case where the nonmagnetic insulating film **120** is formed by stacking the nitride film **441** and the oxide film **442** a plurality of times as shown in Figure **15C**, the type of film at both surfaces of the nonmagnetic insulating film **120** is preferably selected in accordance with the type of each of the soft magnetic film **130** and the ferromagnetic film **190** interposing the nonmagnetic insulating film **120**.

(Example 9)

In a ninth example according to the present invention, a method for producing a magneto-resistive effect memory cell **3101** based on the magneto-resistive effect memory cell **3100** shown in the third example will be described.

With reference to Figure **7**, a nonlinear element **70** formed of a thin film having a P-I-N junction was formed on a substrate. The thin film having a P-I-N junction was produced at a temperature of about 180°C to about 260°C (typically, about 220°C). The P layer, the I layer, and the N layer were produced to have thicknesses of 30 to 50 nm, 300 to 400 nm and 30 to 50 nm, respectively. The laminate was processed into individual elements. The MR portion **100** was formed on the resultant nonlinear element **70** by a method similar to that of the fifth example. Thus, the

magneto-resistive effect memory cell **3100** shown in Figure **7** was produced.

The MR portion **100** having a basic structure of $Ni_{0.1}Fe_{2.9}O_4$ (15)/AlN (1.2)/$Fe_{16}N_2$ (10) was produced using, as sputtering targets, $Ni_{0.1}Fe_{2.9}O_4$ (for the soft magnetic film **130**), Al (for the nonmagnetic insulating film **120**), and $Fe_{16}N_2$ (for the ferromagnetic film **110**). AlN was formed by the method described in the fifth example.

The interface between the AlN film and the $Fe_{16}N_2$ film was observed to be very flat and satisfactory. This reflects a satisfactory junction compatibility of AlN and $Fe_{16}N_2$, which are both nitrides.

Based on the magneto-resistive effect memory cell **3100**, the magneto-resistive effect memory cell **3101** shown in Figure **16A** was produced.

The magneto-resistive effect memory cell **3101** shown in Figure **16A** has the following structure. On a substrate **10**, the MR portion **100** and the nonlinear element **70** are formed. The nonlinear element **70** includes a P layer **11**, an I layer **12** and an N layer **13**. The magneto-resistive effect memory cell **3101** further includes conductive films **140**, **150** and **151** and a contact layer **15** for electrically connecting the MR portion **100** and the nonlinear element **70** and also connecting these elements and an external device. The magneto-resistive effect memory cell **3101** also includes an insulating layer **14**.

The MR characteristics of the magneto-resistive effect memory cell **3101** shown in Figure **16A** were measured

at room temperature at an applied magnetic field of 100 Oe. The MR ratio was about 28%, the tunnel junction area was about 1 μm^2, and the tunnel junction impedance was about 20 Ω.

5

The conductive films **140, 150** and **151** were formed of Au, and the conductive film **170** was formed of AuCr. The insulating film for insulating the MR portion **100** and the conductive layer **170** was formed of an SiO_2 or Si_3N_4 film

10   obtained by plasma CVD.

The operation of the magneto-resistive effect memory cell **3101** produced in this manner was confirmed in the following manner.

15

A pulse current **531** shown in Figure **9A** was caused to flow in the conductive film **170** (word line) to magnetize the hard magnetic film **110** in one direction. Then, a pulse current **532** (upper portion in Figure **9B**) was caused to flow

20   in the conductive film **170**, and a change in the voltage value ($\Delta R_5/\Delta t$) of the magneto-resistive effect memory cell **3101** measured through the conductive films **140** and **150** was monitored. As a result, a voltage change **533** (lower portion in Figure **9B**) corresponding to the written information was

25   detected. Thus, it was found that the desired magneto-resistive effect memory cell **3101** using an insulating film for a nonmagnetic film was realized.

The nonlinear element **70** can have an M-I-S structure

30   described below in a tenth example. As the nonlinear element **70**, any element which exhibits a nonlinear current - voltage characteristic is usable. The MR portion **100** can be replaced with the MR portion **101** (Figure **3**).

In this example, $Fe_{16}N_2$ was used as a nitride for the ferromagnetic film **110**. The magneto-resistive effect memory cell **3101** has been confirmed to perform a desired operation even when FeN_x $(0.1 \le x \le 0.5)$ or $FeMN_y$ $(0.5 \le y \le 1.0)$ is used (M indicates one of Ta, Al, Ni, Pt and Co). In this example, AlN was used as a nitride for the nonmagnetic insulating film **120**. The magneto-resistive effect memory cell **3101** has been confirmed to provide similar characteristics even when other nitrides are used. These results are shown in Table 1.

Table 1

Nonmagnetic insulating film NM	Film thickness (nm)	Element area (μm^2)	Element resistance (Ohm)	Change ratio in magnetic resistance (%)
BN	3	0.64	136	23
InN	3	0.64	104	21
AlN	1.5	0.64	90	29
AlN (O)*	1.5	0.64	165	32
AlN/BN (O)**	2	0.64	180	35

(The MR portion was formed to have a structure of $Ni_{0.81}Fe_{0.19}$ (25)/$Co_{0.5}Fe_{0.5}$ (4)/NM/$Fe_{16}N_2$ (5)/IrMn (25).

* "(O)" indicates that oxidization was performed after nitrided.
** "/" indicates a laminate.

(Example 10)

In a tenth example according to the present invention, a method for producing a magneto-resistive effect memory cell **3102** based on the magneto-resistive effect memory cell **3100** (Figure **7**) shown in the third example will

be described.

The magneto-resistive effect memory cell **3102** shown in Figure **16B** was produced by a method similar to that of the ninth example.

The MR portion **101** having a basic structure of $Fe_{16}N_2$ (10)/AlN (1.8)/$Fe_{16}N_2$ (5)/IrMn (25) was produced using, as sputtering targets, $Fe_{16}N_2$ (for the soft magnetic film **130**), Al (for the nonmagnetic insulating film **120**), $Fe_{16}N_2$ (for the ferromagnetic film **190**), and IrMn (for the magnetization rotation prevention layer as the antiferromagnetic film **180**).

AlN was formed by plasma nitriding using ECR (electron cyclotron resonance). A contact layer **19** was formed of Al, Cr or Ti on the MR portion **101**. A nonlinear element **71** having an M-I-S junction was formed of a-Si on the contact layer **19**. An Si film (S layer) **18** and an insulating film (I layer) **17** were formed to have thicknesses of about 50 nm and about 100 to 200 nm, respectively. A metal film (M layer) **16** was used as a sense line (or a bit line). The nonlinear element **71** was formed in a temperature range of about 180°C to about 260°C (typically, about 220°C).

The interface between the AlN film and the $Fe_{16}N_2$ film was observed to be very flat and satisfactory. This reflects a satisfactory junction compatibility of AlN and $Fe_{16}N_2$, which are both nitrides.

The MR characteristics of the resultant magneto-resistive effect memory cell **3102** were measured at room temperature at an applied magnetic field of 100 Oe. The MR

ratio was about 38%, the tunnel junction area was about 5 μm^2, and the tunnel junction impedance was about 20 Ω. Such superior MR characteristics are considered to be a result of influence of the heat treatment performed for producing

5 the nonlinear element **71**. The magneto-resistive effect memory cell **3102** has an asymmetric current - voltage characteristic shown in Figure **17**. It has been confirmed that the current with respect to the voltage applied to the magneto-resistive effect memory cell **3102** is provided with

10 asymmetric directivity.

The conductive film **150** was formed of TiN. TiN is highly compatible with $Fe_{16}N_2$ and thus contacts $Fe_{16}N_2$ in a satisfactory manner. Therefore, the contact resistance was

15 reduced by about 20% when TiN was used than when Au was used, although TiN has a higher specific resistance than that of Au. The conductive film **170** was formed of AuCr. The insulating film for insulating the MR portion **101** and the nonlinear element **71** and for insulating the nonlinear

20 element **71** and the conductive film **170** was formed of SiO_2 obtained by plasma CVD.

The operation of the magneto-resistive effect memory cell **3102** produced in this manner was confirmed in

25 the following manner.

A pulse current **541** shown in Figure **10A** was caused to flow in the conductive film **170** to magnetize the soft magnetic film **130** in one direction. Then, a pulse current

30 **542** (upper portion in Figure **10B**) was caused to flow in the conductive film **170**, and a change in the voltage value (ΔV_1) of the magneto-resistive effect memory cell **3102** measured through the metal film **16** and the conductive film **150** was

monitored. As a result, a pulse 543 (lower portion in Figure 10B) corresponding to the written information was detected. Thus, it was found that the desired magneto-resistive effect memory cell 3102 was realized.

In this example, a nitride of Fe was used as a ferromagnetic material. The magneto-resistive effect memory cell 3102 has been confirmed to perform a desired operation even when a nitride of Co is used.

(Example 11)

In an eleventh example according to the present invention, a method for producing a magneto-resistive effect memory cell 4000 shown in the fourth example will be described.

The magneto-resistive effect memory cell 4000 shown in Figures 8A through 8D was produced by a method similar to that of the fifth example. The MR portion 200 was produced using, as sputtering targets, $Ni_{0.68}Co_{0.2}Fe_{0.12}$ for the soft magnetic films 132, 133 and 134, Al for the nonmagnetic insulating films 122, 123 and 124, and $Co_{0.5}Fe_{0.5}$ and $Co_{0.9}Fe_{0.1}$ for the hard magnetic films 112, 113 and 114 having different magnetic coersive forces. Under the conditions used by the present inventors to produce the magneto-resistive effect memory cell 4000 in this example, the magnitudes of the magnetic coersive forces had a relationship of $Co_{0.9}Fe_{0.1} <$ $Co_{0.5}Fe_{0.5} < Co$.

The resultant MR portion 200 had a triple-junction array of $Ni_{0.68}Co_{0.2}Fe_{0.12}$ (10)/AlN (1.5)/Co (15)/AlN (15)/$Ni_{0.68}Co_{0.2}Fe_{0.12}$ (10)/AlN (1.5)/$Co_{0.5}Fe_{0.5}$ (15)/AlN (15)/$Ni_{0.68}Co_{0.2}Fe_{0.12}$ (10)/AlN (1.5)/$Co_{0.9}Fe_{0.1}$ (15). AlN was

produced by the method described in the fifth example. The MR characteristics of the MR portion **200** were measured at room temperature at an applied magnetic field of 100 Oe. The MR ratio of the array was about 28%. The tunnel junction
5   area was about 2 μm^2.

The conductive films used as the sense lines and bit lines (conductive films similar to the conductive films **140** and **150**; not shown in Figures **8A** through **8D**) were formed
10   of Au, and the conductive film **172** used as the word lines was formed of AuCr. The insulating film for insulating the MR portion **200** and the conductive film **172** was formed of SiO_2.

15   The operation of the magneto-resistive effect memory cell **4000** produced in this manner was confirmed in the following manner.

A pulse current **551** shown in Figure **18A** was caused
20   to flow in the conductive film **172** to magnetize the hard magnetic films **112**, **113** and **114** in one direction. Then, an inclining pulse current **552** (upper portion in Figure **18B**) was caused to flow in the conductive film **172** to cause inversion of magnetization direction in the hard magnetic
25   films **112**, **113** and **114**, sequentially. Thus, a change in the voltage value V_2 measured through the sense lines and the bit lines was monitored. As a result, a pulse **553** (lower portion in Figure **18B**) corresponding to the written information was detected. Thus, it was confirmed that
30   multiple levels of a signal have been stored in the magneto-resistive effect memory cell **4000**.

The magneto-resistive effect memory cell **4000**

allows multiple levels of a signal to be recorded by applying an appropriate bias voltage. The written information can be detected in accordance with the change in the voltage V_2 under a constant bias voltage.

5

(Example 12)

Figures **19A** and **19B** shows an MRAM **5000** in a twelfth example according to the present invention.

10   The MRAM **5000** includes magneto-resistive effect memory cells **3102** (Figure **16B**) described in the tenth example.

Each magneto-resistive effect memory cells **3102**
15 shown in Figure **16B** was produced by a method similar to that of the tenth example.

The MR portion **101** having a basic structure of $Ni_{0.1}Fe_{2.9}O_4$ (5)/AlN (1.2)/$Fe_{16}N_2$ (10)/IrMn (20) was produced
20 using, as sputtering targets, $Ni_{0.1}Fe_{2.9}O_4$ (for the soft magnetic film **130**), Al (for the nonmagnetic insulating film **120**), $Fe_{16}N_2$ (for the ferromagnetic film **190**), and IrMn (for the magnetization rotation prevention layer as the antiferromagnetic film **180**).

25

AlN was formed by the method described in the fifth example. In this example, a contact layer **19** was formed of Al on the MR portion **101**. A nonlinear element **71** having a P-I-N junction was formed of a-Si on the contact layer **19**.
30 The nonlinear element **71** in this example includes a P layer instead of the Si film (S layer) **18** shown in Figure **16B**, and an N layer instead of the metal film (M layer) **16**.

The nonlinear element **71** was produced in a temperature range of about 180°C to about 260°C (typically, about 220°C). The P layer, the I layer and the N layer were formed to have thicknesses of about 100 to about 200 nm, about 100 to about 200 nm and about 50 nm, respectively.

The interface between the AlN film and the $Fe_{16}N_2$ film was observed to be very flat and satisfactory. This reflects a satisfactory junction compatibility of AlN and $Fe_{16}N_2$, which are both nitrides.

The MR characteristics of the resultant magneto-resistive effect memory cell **3102** were measured at room temperature at an applied magnetic field of 100 Oe. The MR ratio was about 33%, the tunnel junction area was about 2 μm^2, and the tunnel junction impedance was about 100 Ω. Such superior MR characteristics are considered to be a result of influence of the heat treatment performed for producing the nonlinear element **71**. The magneto-resistive effect memory cell **3102** has an asymmetric current - voltage characteristic shown in Figure **17**. It has been confirmed that the current with respect to the voltage applied to the magneto-resistive effect memory cell **3102** is provided with asymmetric directivity.

The MRAM **5000** includes a plurality of magneto-resistive effect memory cells **3102**, each produced as described above, in a matrix of 256 × 256.

In the MRAM **5000**, a conductive film **145** acting as a sense line (or a bit line) which is electrically connected to the N layer of the nonlinear element **71** was formed of Au, the conductive film **170** was formed of AuCr, and the

insulating film for insulating the MR portion **101** and the conductive film **170** was formed of SiO_2.

The conductive films **145** and **150** (bit lines and sense lines), the conductive films **170** (word lines) are arranged in a matrix as shown in Figure **19A**. In Figure **19A**, each conductive film **170** is shown as provided on side surfaces of the respective MR portions **101**. This is for the sake of convenience for easier explanation. As shown in Figure **19B**, the MRAM **5000** in this example includes the conductive films **145** and the conductive films **170** arranged in the same direction with respect to the MR portions **101**. As shown in Figure **19A**, the present invention is applicable to an MRAM having the conductive films **170** provided on side surfaces of the respective MR portions **101**. The conductive films **150** and the conductive films **170** can be provided in the same direction with respect to the MR portions **101**.

Switch sections **401** and **411** for specifying addresses, and signal detection sections **402** and **412** are arranged as shown in Figure **19B**. The switch sections **401** and **411** select arbitrary conductive films **145**, **150** and **170**. The signal detection sections **402** and **412** detect a current value or a voltage value of each conductive film.

Information is written in the MR portion **101** as follows. A current pulse is caused to flow in the conductive film **150** as a row element and the conductive film **170** as a column element, and the magnetization state of only a specific MR portion **101** is changed by the resultant synthesized magnetic field. In this example, the conductive film **150** (bit line or sense line) also acts as a word line.

A read operation of the MRAM **5000** in an arbitrary memory state was confirmed in the following manner.

5   A specific conductive film **145**, a specific conductive film **150** and a specific conductive film **170** were selected by the switch sections **401** and **411**. The resistance value of the MR portion **101** corresponding to the selected conductive films was monitored. As in the second example,

10   the value of the difference between the monitored resistance value of the MR portion **101** and a reference value was monitored through a differential circuit (not shown; preferably built-in in the signal detection sections **402** and **412**). The memory state was read in accordance with the

15   value of the difference.

Since the memory state of the MR portion **101** was stored, the read operation was confirmed to be an NDRO operation.

20

These results showed that the MRAM **5000** according to the present invention was realized.

In this example, the magneto-resistive effect

25   memory cell **3102** having a structure shown in Figure **16B** is described. Alternatively, a desired magneto-resistive effect memory cell and an MRAM according to the present invention can be obtained by using a nonlinear element **71** having a structure as, and located as, the nonlinear element

30   **70** shown in Figure **16A**, and using an MR portion **101** having a structure as the MR portion **100** shown in Figure **16A**. The nonlinear element **71** can have an M-I-S junction shown in Figure **10**. As the nonlinear element **71**, any element which

exhibits a nonlinear current - voltage characteristic is usable. The MR portion **101** can be replaced with the MR portion **100** (Figure 1).

5   (Example 13)

In a thirteenth example according to the present invention, a method for producing the magneto-resistive effect memory cell **1000** shown in the first example will be described.

10

The magneto-resistive effect memory cell **1000** shown in Figure 1 was produced by a method similar to that of the fifth example.

15   Referring to Figure 1, the MR portion **100** shown in Figure 1 was produced using, as sputtering targets, $Co_{0.2}Ni_{0.68}Fe_{0.12}$ (for the soft magnetic film **130**), Al (for the nonmagnetic insulating film **120**), $Co_{0.9}Fe_{0.1}$ (for the hard magnetic film **110**), and $Co_{0.75}Pt_{0.25}$ (for the hard magnetic

20   film **110**). A multi-origin sputtering apparatus (not shown) was used. The basic structure of the MR portion **100** was CoNiFe (15)/AlN(1)/CoFe (5)/CoPt (25).

In this example, the hard magnetic film **110** has a
25   two-layer structure of CoFe/CoPt.

The MR portion **100** having the above-described structure was produced as follows. CoNiFe was deposited on an Si substrate oxidized by heating. Then, the nonmagnetic
30   insulating film **120** was formed by sputtering Al in an (N_2 + Ar) atmosphere. The nonmagnetic insulating film **120** was subjected to spontaneous oxidation in an oxygen atmosphere in a vacuum tank in order to completely insulate a non-

insulating portion of the nonmagnetic insulating film **120** through which microshortcircuiting can occur. Each of a nitriding step and an oxidizing step was performed twice, so as to form the nonmagnetic insulating film **120** having a thickness of about 1 nm. By appropriately controlling such processing, satisfactory tunnel characteristics were obtained. Next, the CoFe and CoPt were deposited on the nonmagnetic insulating film **120**.

CoPt of the resultant MR portion **100** was magnetized, and the MR characteristics of the MR portion **100** were measured at room temperature at an applied magnetic field of 100 Oe. The MR ratio was about 31%. This value was higher than the MR ratio of a similarly structured MR portion including a nonmagnetic insulating film **120** obtained by performing each of a nitriding step and an oxidizing step once. The magnetic field width represented as Hc and generated by the MR portion **100** was 5 Oe to 100 Oe. The tunnel junction area was about 2 μm^2. The impedance of the tunnel junction was about 35 Ω. It was also found that the impedance of the tunnel junction can be controlled in the range of several ohms to several hundred ohms by changing the film formation conditions.

It was found that the yield of tunnel junction formation is improved by subjecting the nonmagnetic insulating film **120** to a nitriding step and an oxidizing step in repetition as in this example and that the production of the present invention is effective for an element having a tunnel junction.

The magneto-resistive effect memory cell **1000** shown in Figure **1** including the MR portion **100** obtained as

described above was produced. The conductive films **140** and **150** for the sense line and the bit line were formed of Pt or Au, and the conductive film **170** for the word line was formed of Al, AuCr, Ti/Au or Cu/Ta. The insulating film for insulating the MR portion **100** and the conductive film **170** was formed of CaF_2 or SiO_2.

The operation of the magneto-resistive effect memory cell **1000** produced in this manner was confirmed in the following manner.

A pulse current **531** shown in Figure **9A** was caused to flow in the conductive film **170** (word line) to magnetize the hard magnetic film **110** in one direction. Then, a pulse current **532** (upper portion in Figure **9B**) was caused to flow in the conductive film **170**, and a change in the voltage value $(\Delta R_5/\Delta t)$ of the magneto-resistive effect memory cell **1000** measured through the conductive films **140** and **150** (sense line and bit line) was monitored. As a result, a pulse **533** (lower portion in Figure **9B**) corresponding to the written information was detected. Thus, it was found that the desired magneto-resistive effect memory cell **1000** was realized.

(Example 14)

In a fourteenth example according to the present invention, a method for producing a magneto-resistive effect head **6000** shown in the third example will be described.

The magneto-resistive effect head **6000** shown in Figures **20A** and **20B** was produced by a method similar to that of the fifth example. Figure **20A** is an isometric view of the magneto-resistive effect head **6000**, and Figure **20B** is

a cross-sectional view thereof.

The MR portion **101** having a basic structure of NiFe (20)/CoNiFe (8)/AlN (0.6)/CoFe (6)/IrMn (25) was produced using, as sputtering targets, $Ni_{0.81}Fe_{0.19}$ and $Ni_{0.68}Co_{0.2}Fe_{0.12}$ (for the soft magnetic film **130**), Al (for the nonmagnetic insulating film **120**), $Co_{0.75}Fe_{0.25}$ (for the ferromagnetic film **190**), and IrMn (for the magnetization rotation prevention layer as the antiferromagnetic film **180**).

The nonmagnetic insulating film **120** was formed by sputtering Al in an (N_2 + Ar) atmosphere. The MR characteristics of the resultant MR portion **101** were measured at room temperature at an applied magnetic field of 100 Oe. The MR ratio was about 25%. The tunnel junction area was about 3 μm^2. The impedance of the tunnel junction was about 10 Ω.

The magneto-resistive effect head **6000** including the MR portion **101** thus obtained was produced.

With reference to Figures **20A** and **20B**, the magneto-resistive effect head **6000** includes a substrate **601**, for a slider, formed of a sintered material containing $Al_2O_3 \cdot$ TiC as a main component, shield layers **602** and **603**, writing magnetic poles **605** and **606** formed of an NiFe alloy, a coil **607** formed of Cu, and gap layers **608** formed of Al_2O_3. The gap layers **608** are located between two adjacent layers. The shield layers **602** and **603** each have a thickness of about 1 μm. The writing magnetic poles **605** and **606** each have a thickness of about 3 μm. The gap layers **608** of Al_2O_3 between the shield layer **602** and the MR portion **101** and between the shield layer **603** and the MR portion **101** each have a thickness

of about 0.1 μm, and the gap layer **608** between writing magnetic poles **605** and **606** is about 0.2 μm. The distance between the conductive layer **150** and the writing magnetic pole **605** is about 4 μm, and the coil **607** has a thickness of about 3 μm.

The MR portion **101** is located between the shield layers **602** and **603**, and is not exposed to a surface **604** of the magneto-resistive effect head **6000**.

A bias current is applied to the MR portion **101** through the conductive films **141** and **150**. The soft magnetic films **130** and the ferromagnetic film **190** which are located so as to interpose the nonmagnetic insulating film **120** are set to have magnetization directions directed perpendicular to each other. Thus, changes in the magnetization direction corresponding to reproduction signals are detected at a sufficiently high sensitivity.

As shown in Figures **21A** and **21B**, a magnetic disk apparatus **7000** including magneto-resistive effect heads **6000** was produced. Figure **21A** is a plan view of the magnetic disk apparatus **7000**, and Figure **21B** is a cross-sectional view of the magnetic disk apparatus **7000**.

A magnetic recording medium **701** is formed of a Co-Ni-Pt-Ta alloy. The magneto-resistive effect head **6000** is supported by a magnetic head supporting section **702**, and driven by a magnetic head driving section **703**. The tracking width of the magneto-resistive effect head **6000** is set to be 5 μm. As shown in Figure **21B**, the magnetic disk apparatus **7000** includes a plurality of magneto-resistive effect head **6000** having the above-described structure.

The magneto-resistive effect head **7000** according to the present invention has a higher resistance change ratio than a GMR magneto-resistive effect head which is a conventional CIPMR element. Accordingly, the magneto-resistive effect head **6000** has a sufficiently large reproduction output and thus is very effective as a magnetic head for reproduction. The magneto-resistive effect head **6000** also has a lower impedance. Since the resultant magnetic disk apparatus **7000** detected voltage changes corresponding to the information recorded in the magnetic recording medium **701** in a satisfactory manner, it was found that the magneto-resistive effect head **6000** according to the present invention was realized.

The MR portions **100**, **101**, **102** and **200** described in all the examples in this specification are usable as a magneto-resistive effect head as described in this example.

INDUSTRIAL APPLICABILITY

As described above, according to the present invention, a magneto-resistive effect memory cell and a magneto-resistive effect head both having satisfactory tunnel characteristics can be produced by using an insulating film of a nitride as a nonmagnetic insulating film. In the case where the ferromagnetic film is also formed of a nitride, the quality of the tunnel junction interface is improved, which is more preferable.

A magneto-resistive effect memory cell, a magneto-resistive effect head, and a method for producing the same according to the present invention allow the

impedance of the tunnel junction to be low. Therefore, a magneto-resistive effect memory cell and a magneto-resistive effect head having a very fine pattern can be provided.

A feature of the present invention is to use a nitride for a nonmagnetic insulating film, and also for a magnetic film. In this manner, a magneto-resistive element, a magneto-resistive effect magnetic head, a magneto-resistive effect memory element, and a high density magneto-resistive effect memory device including such magneto-resistive effect memory elements in a matrix, which have a reduced tunnel junction resistance and an ideal tunnel junction interface, are provided.

Especially, the nonmagnetic insulating film is formed of a combination of a nitride and an oxide. Thus, the advantage of a low tunnel junction resistance of the nonmagnetic insulating film formed of a nitride can be used. In addition, an incompletely nitrided portion of the nonmagnetic insulating film, which tends to be made as a result of dispersion in the production conditions, is oxidized so as to increase the resistance of the incompletely nitrided portion. Thus, a leak conveying path or a hopping conveyance path can be prevented from appearing. In the case where the nonmagnetic insulating film is formed by repeating a nitriding step and an oxidizing step in repetition, the controllability of the tunnel characteristics can be further improved.

According to the present invention, a low junction resistance, which is equivalent to a tunnel junction resistance obtained by using Al_2O_3 for the nonmagnetic

insulating film, is realized with a thicker nonmagnetic insulating film. Therefore, the MR portion can be more easily produced, which is advantageous in uniformizing the characteristics of memory cells which are required to be

5   highly integrated.